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VARIABLE RELUCTANCE PRESSURE TRANSDUCER DEVELOPMENT

By

W. E. Smotherman and W. V. Maddox
von Kármán Gas Dynamics Facility
ARO, Inc.

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a subsidiary of Sverdrup and Parcel, Inc.

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ABSTRACT

Pressure is one of the fundamental aerodynamic parameters which must be measured in hypervelocity wind tunnel testing. Pressure transducers whose time response and pressure ranges are suitable for test section measurements in the hypervelocity tunnels of the von Kármán Gas Dynamics Facility (VKF) have been developed by the Instrumentation Branch of that facility. A description of these transducers, their theory of operation, and their performance characteristics are presented herein.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

Jay T. Edwards, III
Capt, USAF
Gas Dynamics Division
DCS/Research

Donald R. Eastman, Jr.
DCS/Research

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1.0 INTRODUCTION

The necessity to measure pressures ranging from 0.001 psia to 0.10 psia in hotshot tunnels in the von Kármán Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), United States Air Force (useful run times of approximately 40 msec) led to the development of a low pressure wafer gage. Such a unit fabricated from an 80 percent nickel alloy (Hy-Mu "80")* is discussed in AEDC-TR-60-11.* After extensive investigations, it was found that this unit was extremely sensitive to coil geometry, therefore, the performance characteristics are unpredictable. Because of this undesirable characteristic, the transducer has been abandoned, and a wafer gage fabricated from "invar"†, a 36 percent nickel alloy, has replaced it as the standard low pressure measuring device for model instrumentation.

Although the overall performance of the invar wafer gage is adequate for most applications, a faster response gage was required for some types of tests. The location of the diaphragm in this gage was such that its susceptibility to vibrations was greatly increased, and hence acceleration compensation was incorporated within the transducer. This unit is referred to as the low pressure, acceleration compensated transducer.

This report is divided into two sections. Section 2.0 is a discussion of the low pressure wafer gage and section 3.0, of the high response, low pressure, acceleration compensated transducer.

2.0 THE LOW PRESSURE WAFER GAGE

2.1 DESCRIPTION AND THEORY OF OPERATION

The low pressure wafer gage, (Fig. 1), is in the shape of a thin wafer. An assembly section of this unit showing the arrangement of the outer shell halves, diaphragm, and coils is given in Fig. 2. The outer shell halves and the diaphragm are fabricated from a low expansion

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*W. E. Smotherman, "A Miniature Wafer-Style Pressure Transducer," AEDC-TR-60-11, October 1960.

†Carpenter Steel Company, Reading, Pennsylvania.

Manuscript received May 1963.

36 percent nickel alloy, and the overall dimensions of the transducer are 0.575-in. diameter by 0.186-in. thick excluding pressure ports. The weight of this unit is approximately 5.1 gm.

The internal volume for each side of this gage (excluding pressure port) is approximately 1.65×10^{-4} in.^{3} for the machined potting unit and approximately 4.5×10^{-4} in.^{3} for the meniscus potted one. The natural frequency of the 0.0015-in.-thick diaphragm is approximately 3500 cps.

The transducer is coated with a varnish type sealing agent to prevent leakage from the transducer pressure cavities. An internal seal, to prevent leakage between the pressure cavities, is accomplished by a smooth, compression fit between the transducer halves and the diaphragm. Photographs of the transducer parts are shown in Figs. 3 and 4.

The low pressure wafer gage is a half-bridge (Fig. 5) variable reluctance device consisting of a pressure sensing diaphragm of magnetic material, the deflection of which controls the air gap in each of two magnetic circuits. These gaps change in opposite directions and hence produce corresponding changes in the inductance of two pickoff coils. The magnetic circuits are formed by the outer shell halves, the air gap, and the diaphragm; and the flux in these circuits is produced by the 5-v (rms), 20-kc powered coils embedded within the transducer halves. A more detailed treatment of this variable reluctance theory is presented in AEDC-TR-60-11.

2.2 PERFORMANCE CHARACTERISTICS

2.2.1 Sensitivity

The output from the low pressure wafer gage transducer is approximately 100 mv for the full-range (0.10-psid) pressure. This sensitivity and the flexibility of the associated readout system allow calibration of this particular range transducer for full-scale output at 0.001 psid (50μ Hg). With a typical low pressure wafer gage and its associated instrumentation (Fig. 6) calibrated for full-scale output at 0.001 psid, the signal to noise ratio is approximately 50 to 1.

A typical oscillograph trace taken during a hypervelocity tunnel run is shown in Fig. 7. The pressure sensitivity employed here is 0.0032 psid/in. deflection with the absolute value of the pressure ranging from 0.0017 to 0.0023 psia during the useful tunnel run.

2.2.2 Linearity and Hysteresis

A calibration curve such as Fig. 8 may be used to determine the linearity and hysteresis errors of a low pressure wafer gage. A nominal value for these combined errors, which is the maximum deviation from the best straight line drawn from zero to full-scale output, is ±1.0 percent. No gage is accepted for tunnel instrumentation if the combined linearity and hysteresis error exceeds ±2.0 percent.

2.2.3 Temperature and Density Effects

Because this pressure transducer was designed for use in hypervelocity tunnels, only temperature changes which are self-induced by the transducers' electrical power dissipation are of serious concern. At an environmental pressure level of approximately 10μ Hg (absolute), this self-induced temperature rise is approximately 5°F. With an atmospheric environmental pressure, the temperature rise is approximately 3°F.

The low pressure wafer gage was evaluated with the apparatus shown in Fig. 9 to determine the effect of environmental density level changes upon the transducers' output characteristics. From the calibration curve shown in Fig. 10, it can be seen that the sensitivity change caused by a density level change from 10μ Hg to atmospheric pressure (and its associated temperature change) is 2 percent or less. This value is typical of all low pressure wafer gages built to date.

An investigation of the output characteristics of this gage over a greater temperature range revealed that in the region from 75°F to 110°F the temperature sensitivity is approximately 0.3 percent/°F.

2.2.4 Response Time

A response time study of a variety of pressure ports and pressure cavity configurations which may be employed with wafer transducers has been made. A step function generator was developed for this study. In brief, this unit (Fig. 11) operates as follows: dental dam (thin sheet rubber) with an initial thickness of 0.005 in. is stretched and placed between the two chambers as a diaphragm, and both chambers are pumped down to the pressure level at which the rise time is to be determined. The valve in the pressure line to the lower chamber is closed, and the upper chamber is pumped down to a pressure level that is as low as practical (approximately 2 to 10μ Hg). An electric current is passed through a short length of wire, which is pressed against the diaphragm, heating it and causing the diaphragm to rupture. The result is a rapid increase in pressure in the upper chamber. Measurements made with microphones and flush diaphragm transducers indicate that the pressure rise occurs in less than 0.1 msec. It should be noted that rise time in this report is taken as being the time required to reach 95 percent of the final value. The useful range of this generator is 0.0005 to 0.5 psia.

The significant wafer type transducer configurations whose rise times have been measured are shown in Fig. 12, and Fig. 13 is a plot of the results. Shown in Fig. 12b is a flush-mounted unit in which the cavity potting has been allowed to cure naturally so that a meniscus shape (Fig. 14) is formed at the top. This transducer has an inside pressure port diameter of 0.040 in. To determine the effect of port length on the rise time, this same transducer was checked with a 1/2-in. tubing length inserted between the transducer and the orifice (Fig. 12a). Figure 13 (curves A and B) reveals a substantial decrease in rise time for the flush-mounted condition.

Rise times for additional transducer configurations (Figs. 13, curves C and D) have been determined. These transducers have the internal potting machined to give a constant distance of 0.0014 in. between the potting and the diaphragm (Fig. 15). Their respective inside port diameters are 0.046 and 0.052 in.

As a result of measurements of these and other similar transducer configurations, a design for the low pressure wafer gage was found which is considered near optimum. It has an 0.067-in. I. D. pressure port, and the cavity potting geometry is of the meniscus type. In this design, care has been taken to ensure that the opening through the potting connecting the port and the space between the diaphragm and the potting is smooth and free of restrictions. With this transducer mounted as shown in Fig.12e, the rise time at 0.001 psia (Fig. 13, curve E) is approximately 4 msec.

To give an indication of the shape of the response curves, some typical traces of the low pressure wafer gage outputs are shown in Fig. 16.

2.3 INSTRUMENTATION SYSTEM

A block diagram of the complete instrumentation system employed with the low pressure wafer gage is shown in Fig. 6. In this system the transducer coils are connected into an a-c bridge circuit so that they comprise adjacent arms of the bridge. Then, the output signal from the bridge network is directly proportional to the pressure differential applied to the transducer. A carrier amplifier system is used to provide a constant 5-v (rms) 20-kc, supply voltage for the bridge, as well as amplification and demodulation of the transducer signal. The signal is time resolved on a recording oscillograph employing a light beam type galvanometer.

2.4 CALIBRATION

For maximum accuracy the pressure calibrations must be made with the transducer in its test position and at test conditions. The calibration procedure is as follows: with the low pressure wafer in place for a tunnel run, the tunnel is evacuated to run density. Then, small volumes of atmospheric pressure are valved into the tunnel to produce pressure differential steps of approximately 0.001 psi (50μ Hg). These pressure differentials are measured with a precision micromanometer, and the reference pressure is measured with a thermocouple type vacuum gage. Galvanometer deflections which correspond to these pressure steps are recorded.

This calibration technique eliminates both the temperature effect caused by self-heating at low density and the erratic pressure variations which prevail at ambient atmospheric conditions. A typical "in tunnel" static pressure calibration is given in Fig. 17.

3.0 THE LOW PRESSURE, ACCELERATION COMPENSATED TRANSDUCER

3.1 DESCRIPTION AND THEORY OF OPERATION

An assembly section of the low pressure, acceleration compensated transducer is shown in Fig. 18. The outer shell components and the diaphragms are fabricated from the same alloy as used for the low pressure wafer gage. The overall dimensions of this unit are 0.575 in. in diameter by 0.332 in. thick, excluding pressure ports. The weight of this transducer is 9.3 gm.

The pressure cavity of this unit has a volume of approximately 1.65 x 10^{-4} in.^{3}, excluding the pressure port. The natural frequency of the 0.0015-in.-thick diaphragm is approximately 3500 cps. Pressure sealing of this transducer is accomplished by the same technique as that used for the wafer gage. Photographs of this transducer are shown in Figs. 19, 20, and 21.

The low pressure, acceleration compensated transducer, like the low pressure wafer gage, is a variable reluctance device and therefore is governed by the same principles of operation. This transducer is actually made of two half-bridge units (Fig. 22); one is a pressure sensor, and the other is an acceleration sensor.

By referring to Fig. 18, it can be seen that this transducer has been designed to minimize the rise time. The installation technique (Fig. 18) employed allows the transducer to perform in a manner approaching that of a flush diaphragm transducer so that a further decrease in rise time is obtained.

With the transducer mounted as mentioned above, it can be seen that when the model-transducer system vibrates normal to the model surface, the pressure sensing diaphragm and the acceleration sensing diaphragm both act as accelerometer masses, and hence a deflection of each results. The electrical signals produced by these respective deflections will be unequal because of the slight differences in the physical and electrical characteristics of the two units of the transducer. However, each of the signals may be amplified so that they are equal. After amplification, the signals may be introduced into a summing and filtering network (Fig. 23) which algebraically adds them. By properly phasing the signals (180° out of phase) and maintaining them at equal amplitudes, their sum may be made equal to zero. Therefore, any vibration of the transducer produces two signals which cancel each other.

Figure 24b shows the theoretical signal produced by an applied pressure differential input plus a superimposed vibration. In Fig. 24c the signal produced by the accelerometer, whose diaphragm is subjected to no pressure differential, is shown. It can be seen that reversing the polarity of the accelerometer signal and adding it to the pressure transducer signal will produce the theoretical sum shown in Fig. 24d.

3.2 PERFORMANCE CHARACTERISTICS

3.2.1 Sensitivity

The full-range (0.1-psid) output of the low pressure, acceleration compensated transducer is approximately 60 mv. This sensitivity permits the transducer to be calibrated for full-scale output at 0.001 psid. A typical acceleration compensated transducer with its associated instrumentation (Fig. 25) calibrated for full-scale output at 0.0015 psid has a signal to noise ratio of 30 to 1.

3.2.2 Linearity and Hysteresis

The linearity and hysteresis characteristics of the low pressure, acceleration compensated transducer can be examined in Fig. 26. A nominal value for these combined errors (maximum deviation from the best straight line drawn from zero to full-scale output) is ±1.0 percent. No transducer is accepted for tunnel instrumentation if these combined errors exceed ±2.0 percent.

3.2.3 Temperature and Density Effects

Since this transducer was designed for hotshot type tunnel instrumentation, only self-induced temperature changes produced by the transducer's excitation are of serious concern. At an environmental pressure level of approximately 10μ Hg (absolute) the self-induced temperature rise is approximately 5°F, and at an atmospheric environmental pressure level this temperature rise is approximately 3°F.

In determining the effects of a density change upon the transducer's operation, the sensitivity was measured at a low density (10μ Hg) environmental and reference pressure and also at atmospheric conditions. The results of this evaluation, shown in Fig. 27, reveal that the sensitivity change caused by this density level change (and its associated temperature change) is 2 percent or less. This value is typical for all units built to date.

By evaluating this transducer over a greater temperature range, it was found that in the region from 75°F to 110°F the temperatures sensitivity is approximately 0.3 percent/°F.

3.2.4 Response Time

The response time of the low pressure, acceleration compensated transducer was determined in the same manner and with the same equipment as that discussed for the low pressure wafer gage.

The response time of two configurations of this transducer was investigated, and the results are given in Fig. 28. Figure 29 shows a unit in which the potting has been machined to give a constant distance of 0.0014 in. between the potting and the diaphragm. The response time versus pressure level of this particular configuration is given in Fig. 28, curve A. To improve the response characteristics of this transducer, two diagonal grooves were cut in the potting and core (Fig. 30) of a unit identical to the one mentioned above. It is evident from Fig. 28 that this modification significantly reduced the response time of the transducer. It should be noted that rise time is taken as being the time required to reach 95 percent of the final value.

Limitations on the system rise time are imposed by the filter which is employed to attenuate the 3500-cps signal (transducer diaphragm resonant frequency) from the transducer. Measurements in the pressure range from 0.001 to 0.2 psia have shown that with this filter the minimum possible rise time is 0.5 msec. This value is approximately constant throughout the entire pressure range since the filter is the limiting factor.

Typical transducer output traces which present the shape of the response curves are shown in Fig. 31.

3.3 INSTRUMENTATION SYSTEM

A block diagram of the instrumentation system for the low pressure, acceleration compensated transducer is given in Fig. 25. Two carrier-amplifier channels are required; one for the pressure sensor and one for the accelerometer. These units provide a regulated 5-v (rms) 20-kc excitation, amplification, and demodulation. The summing and filtering network shown in Fig. 23 not only provides a means of adding the pressure and acceleration signals; it is designed to properly match the output impedance of the carrier amplifiers and to filter the outputs to substantially reduce the diaphragm natural frequency oscillations on the oscillograph traces. The recording oscillograph employed is a light-beam type with galvanometer possessing a natural frequency of 200 cps.

3.4 CALIBRATION

To acceleration compensate this transducer, it is necessary to produce vibration in the model transducer system while it is located in its test position and to apply the vibration at test conditions (low density) because of the undesirable acoustics of the tunnel at atmospheric pressure. To produce these vibrations, a shaker motor is attached to the back of the model. The frequency of the shaker is then adjusted to the natural frequency of the model support system. With the carrier-amplifier pressure channel gain controls set at the value to be used for the test run, the accelerometer channel gain controls are adjusted to the position which produces a minimum deflection of the galvanometer when the transducer is vibrated.

The pressure calibration of the acceleration compensated transducer is made in the same manner as that of the low pressure wafer gage. With the tunnel evacuated to run density, volumes of atmospheric pressure are valved into the tunnel to produce pressure differential steps of approximately 0.001 psi. These pressure differentials are measured with a precision micromanometer, and the reference pressure is measured with a thermocouple type vacuum gage. The results of a static pressure calibration made in this manner are shown in Fig. 32.

4.0 TUNNEL EVALUATION

A flat plate pressure model designed for viscous interaction studies has recently been tested in The 50-Inch Hypervelocity Tunnel (H) at the AEDC. This model was instrumented with eight low pressure wafer gages and seven low pressure, acceleration compensated transducers. During the test, 28 tunnel runs were conducted and pressures ranging from 0.0016 to 0.1 psia were measured. At the lower pressures (0.0016 to 0.01 psia) the agreement between transducers was ±10 percent or less, and the agreement between the measured pressures and the theoretical pressures was also within ±10 percent. At the higher pressures (0.01 to 0.10 psia) these agreements were somewhat improved, being within ±5 percent. It is estimated that the inaccuracy of the micromanometer at 0.001 psid is approximately 6 percent. This could account in part for the disagreements between the measured and theoretical pressures.

By referring to Fig. 33, a comparison of an acceleration compensated transducer and a unit whose compensating system is not employed can be made. These two traces were taken during a tunnel run in which both transducers were subjected to the same vibrations. It is evident that the acceleration compensating system substantially reduces the magnitude of oscillations which appear on the pressure data oscillograph traces as a result of model and transducer vibration. This improvement permits a more accurate reduction of the pressure data from the traces since less curve fairing is required.

During these tunnel tests, it was found that although the low pressure wafer gage is not acceleration compensated, it can be mounted in such a manner as to virtually eliminate the acceleration effect. With the transducer installed so that the plane of the diaphragm is parallel with the plane of the vibrations, these vibrations have a negligible effect upon the pressure data traces (Fig. 7). Although the rise time of this transducer and its mounting configuration is longer than that of the acceleration compensated unit (Figs. 13 and 8), it is adequate for most hotshot tunnel applications.

5.0 CONCLUSIONS

Tunnel data, substantiated by laboratory performance data, have indicated that the low pressure wafer gage and the low pressure, acceleration compensated transducer can be used to measure pressures ranging from 0.001 to 0.10 psia in hypervelocity tunnels. At these pressure levels, the response of these transducers is adequate for pressure measurements in such wind tunnels. Since, in most applications, the low pressure wafer gage can be mounted so that vibration is of little consequence, it can generally replace the low pressure, acceleration compensated, high response transducer.

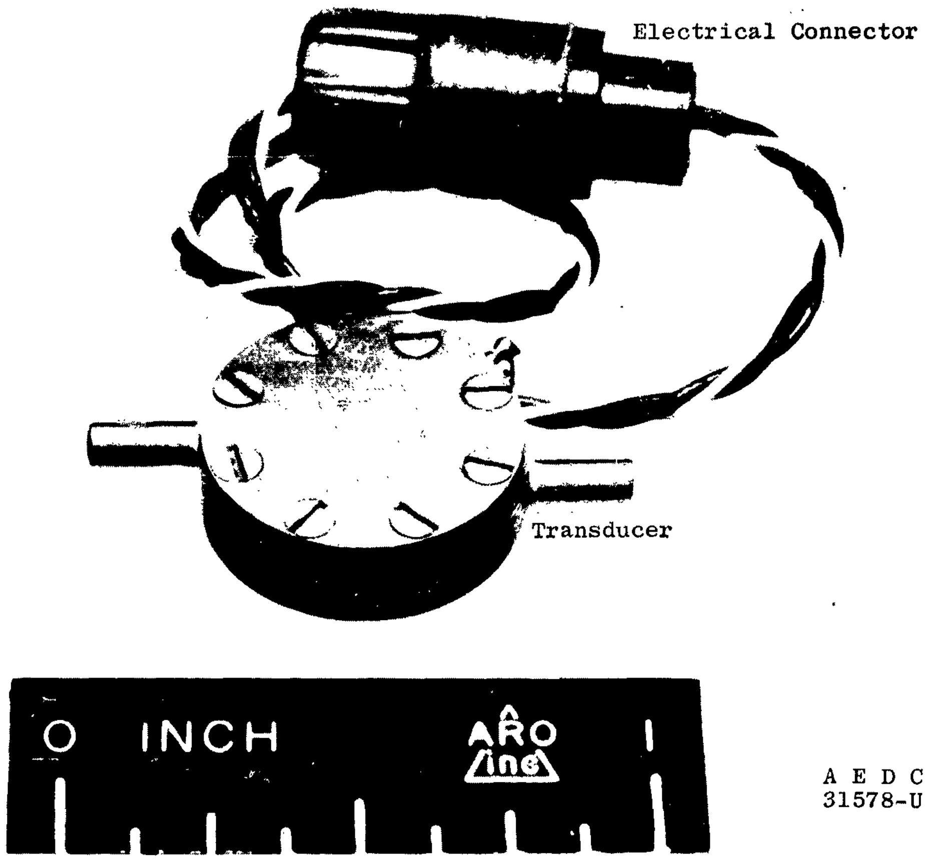


Fig. 1 The Low Pressure Wafer Gage

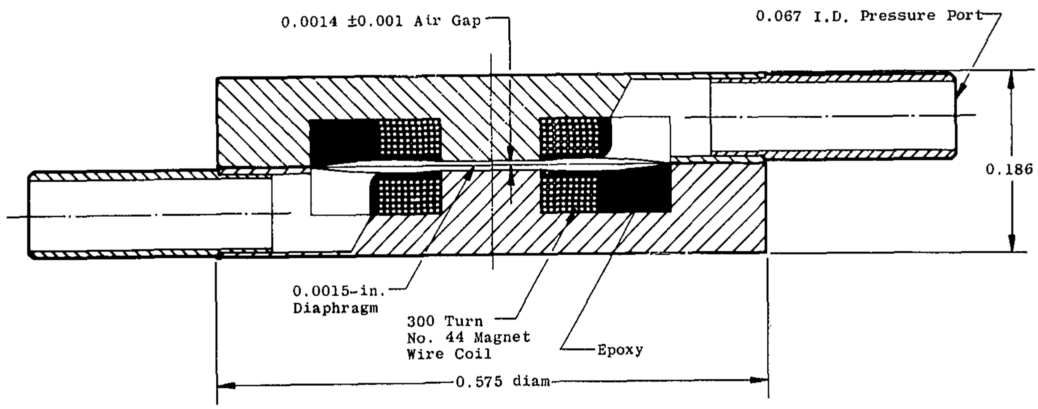


Fig. 2 Assembly Section of the Low Pressure Wafer Gage

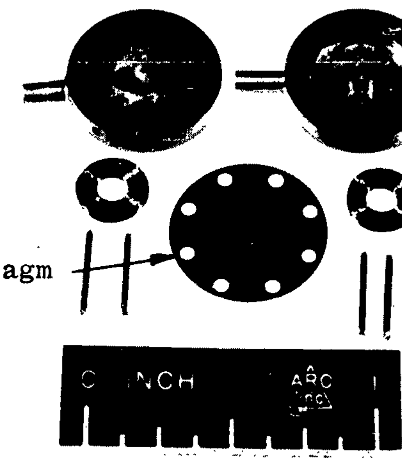


Fig. 3 Wafer Gage Components

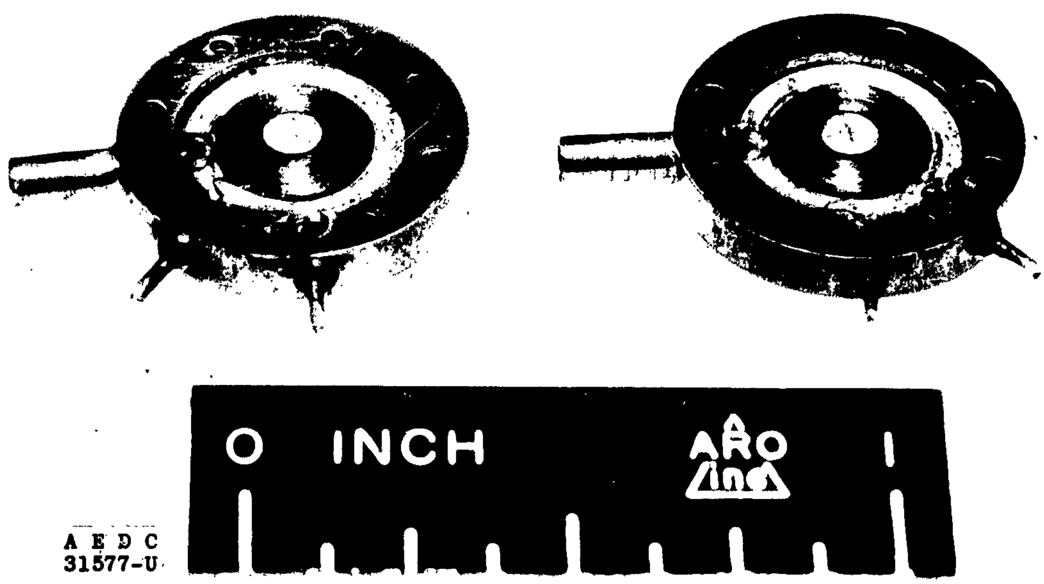


Fig. 4 Wafer Gage Outer Shell Halves with Embedded Coils

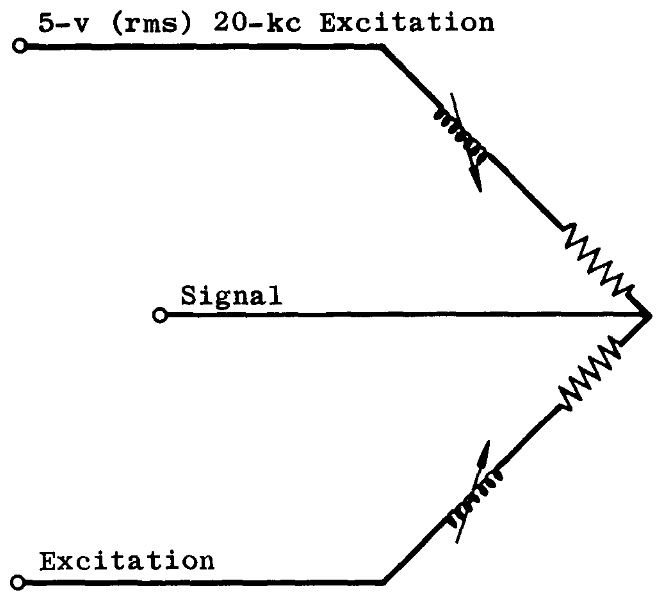


Fig. 5 Low Pressure Wafer Gage Schematic

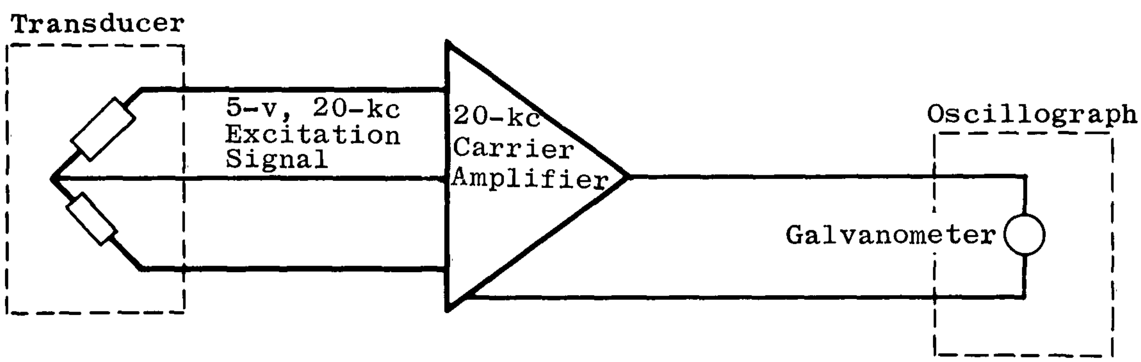


Fig. 6 Low Pressure Wafer Gage Instrumentation System

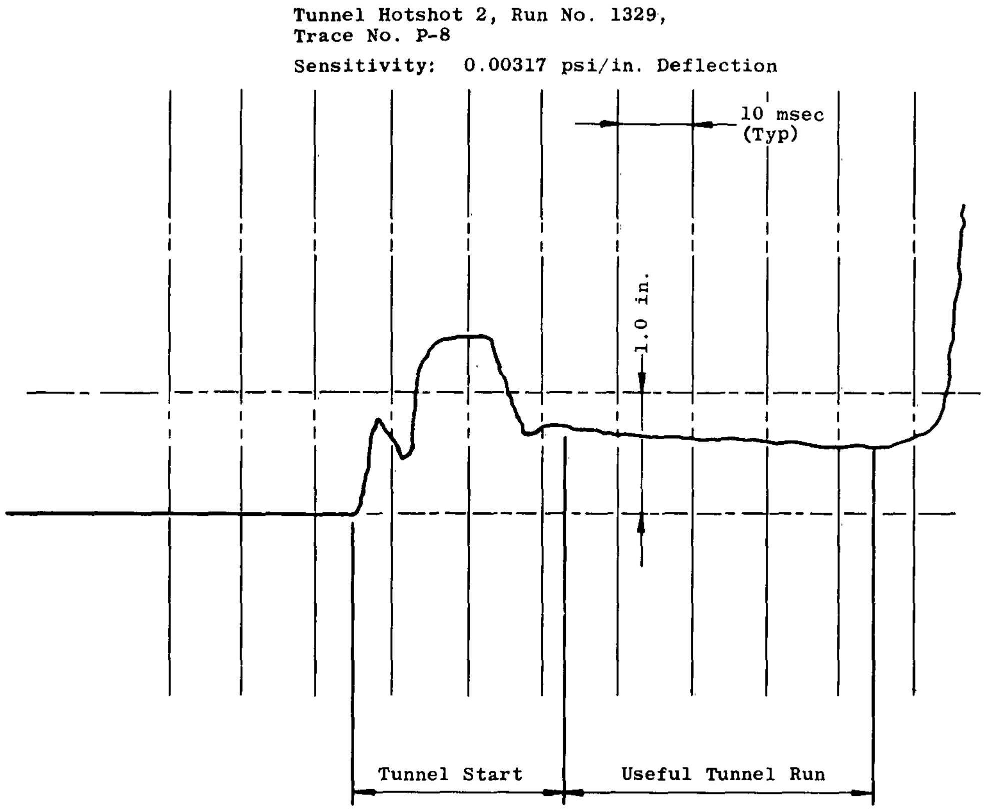


Fig. 7 Typical Oscillograph Trace of Low Pressure Wafer Gage Output during Tunnel Run

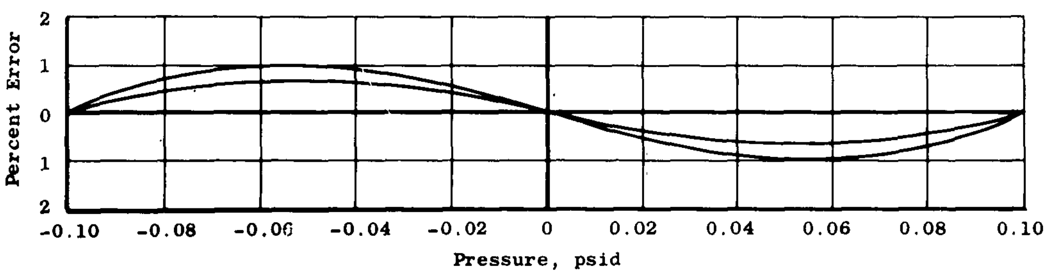


Fig. 8 Wafer Gage Linearity and Hysteresis

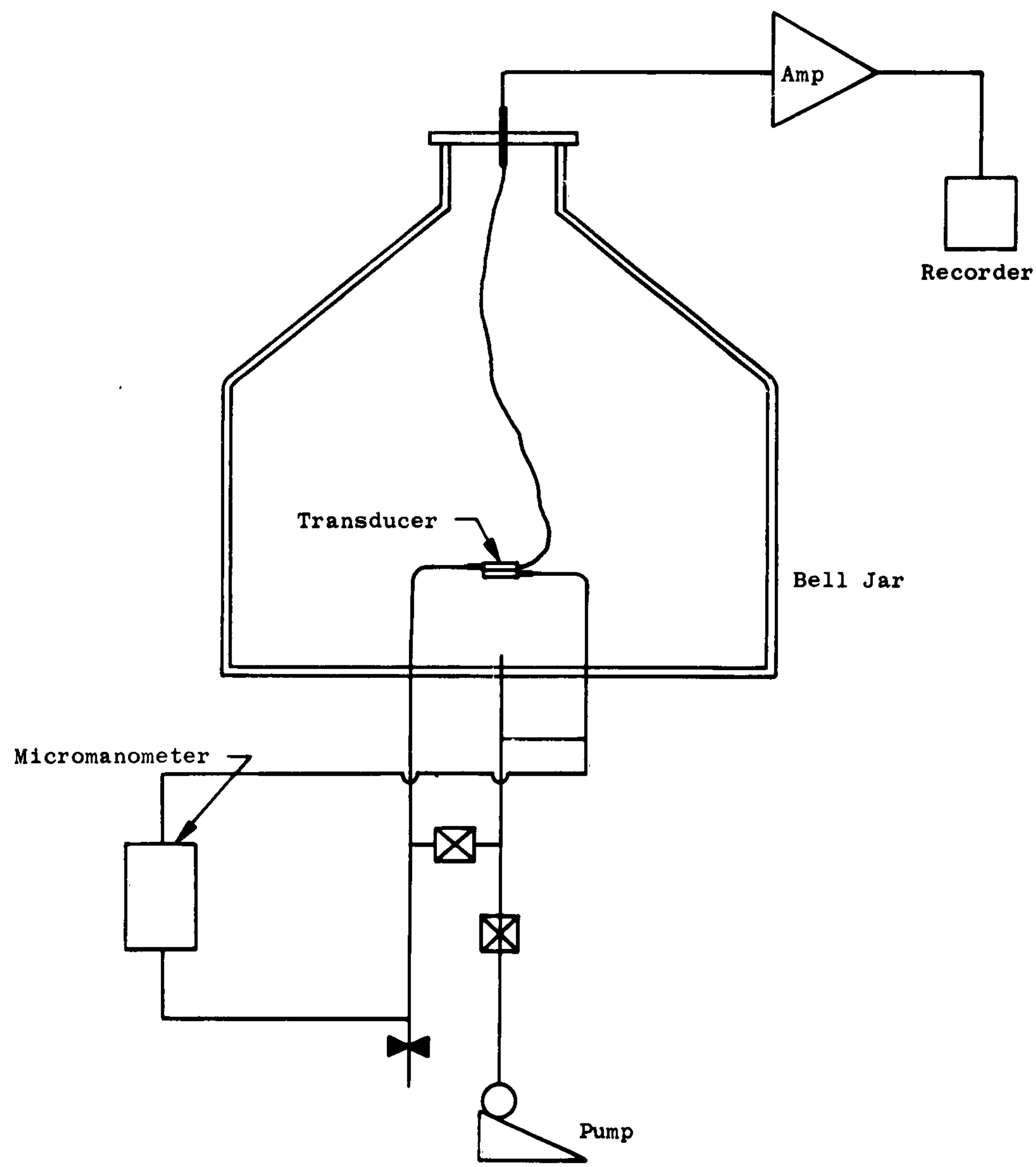


Fig. 9 Transducer Pressure Environment System

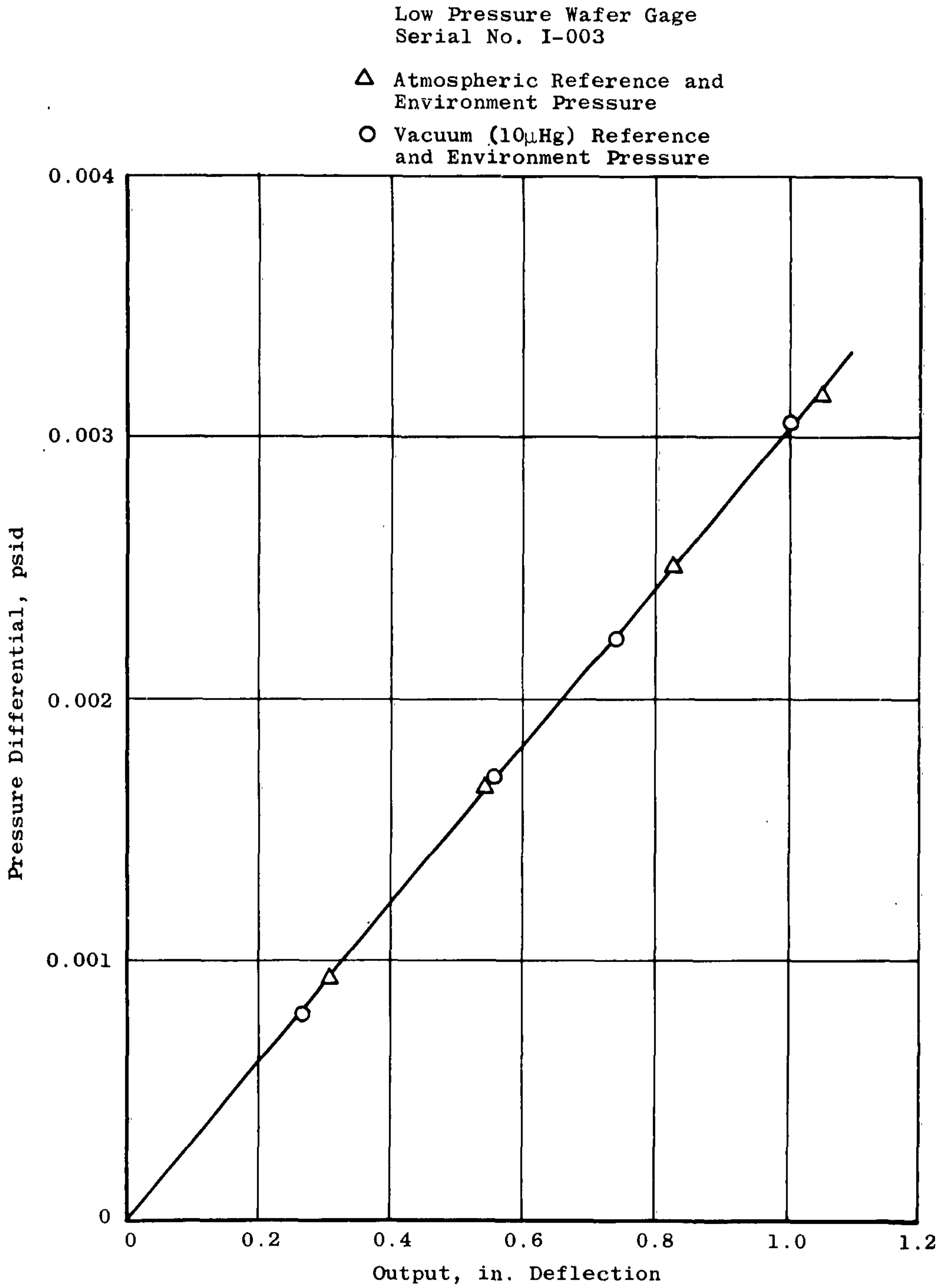


Fig. 10 Effect of Density Change on Low Pressure Wafer Gage Output

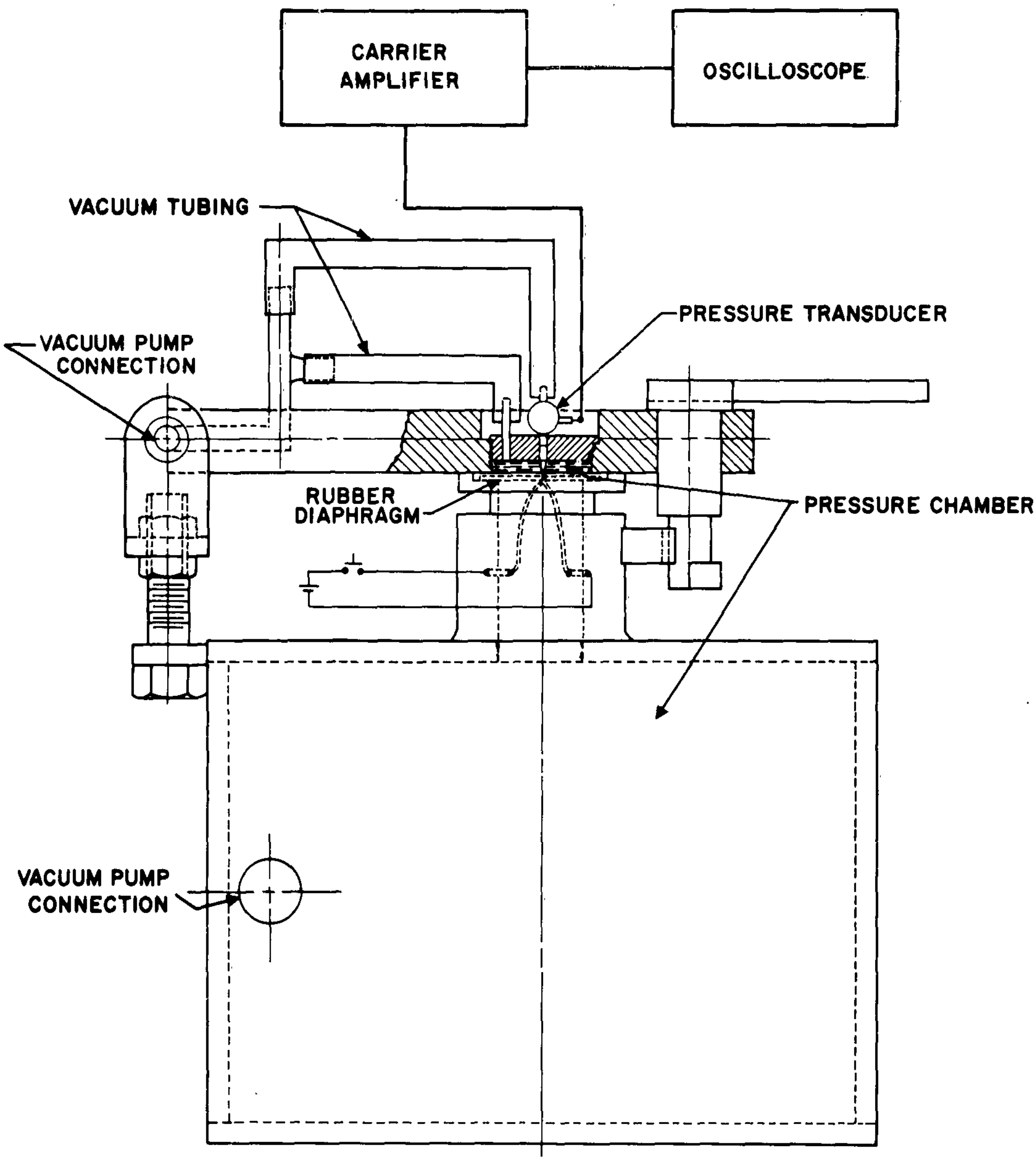
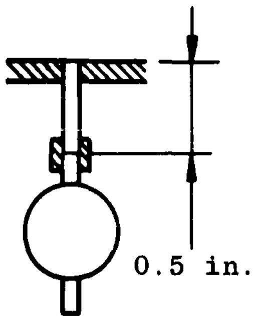
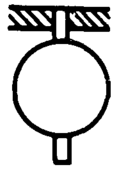


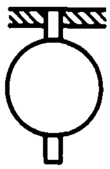
Fig. 11 Low Pressure Step-Function Generator



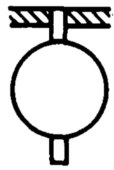
a. 0.040-in. I. D. Port
(Meniscus Potting)



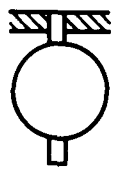
b. 0.040-in. I. D. Port
(Meniscus Potting)



c. 0.046-in. I. D. Port
(Machined Potting)



d. 0.052-in. I. D. Port
(Machined Potting)



e. 0.067-in. I. D. Port
(Meniscus Potting)

Fig. 12 Response Study Configurations of Low Pressure Wafer Gage

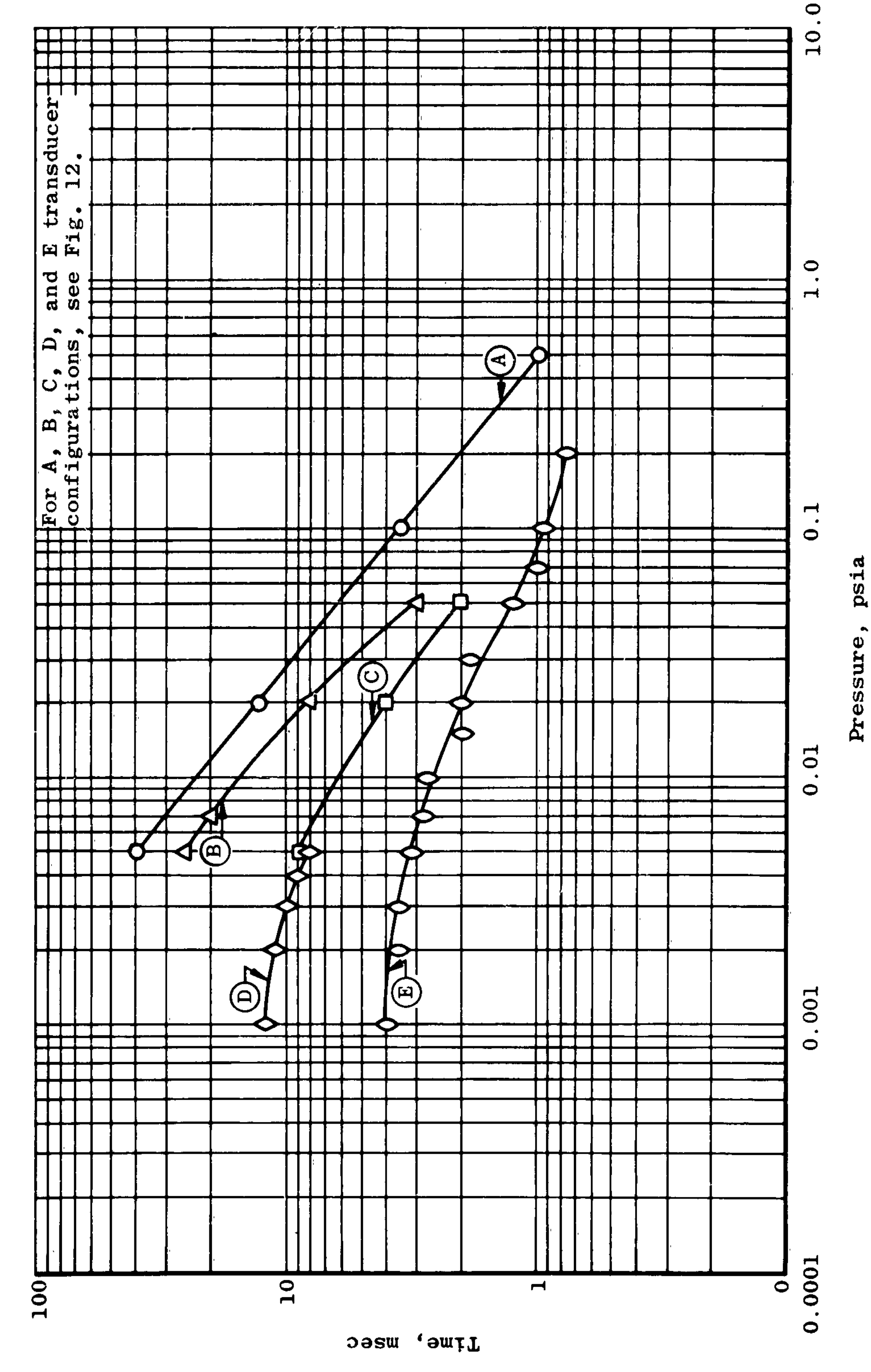


Fig. 13 Low Pressure Wafer Gage Response Time

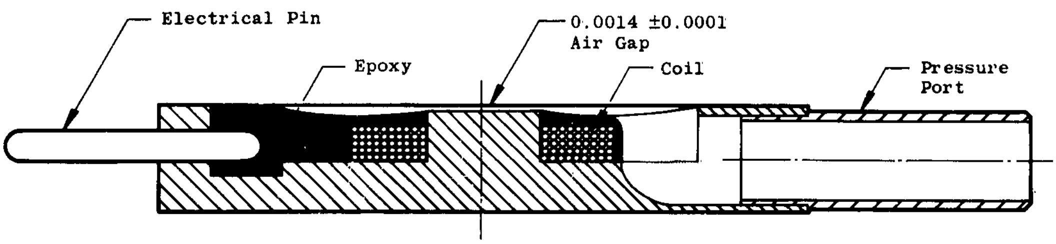


Fig. 14 Wafer Gage Half with Meniscus Potting

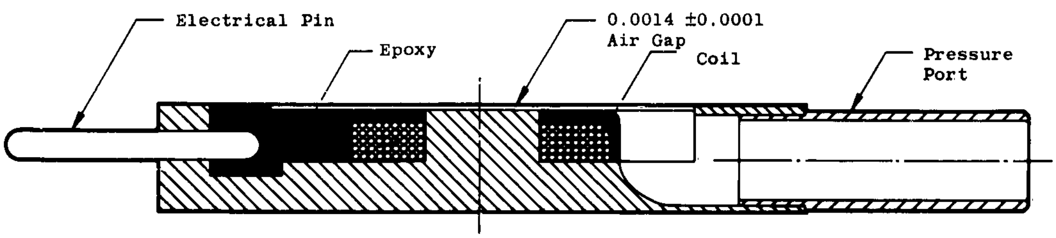
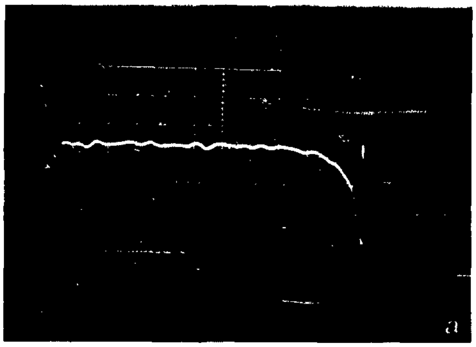


Fig. 15 Wafer Gage with Machined Potting

Configuration "E" of Fig. 12

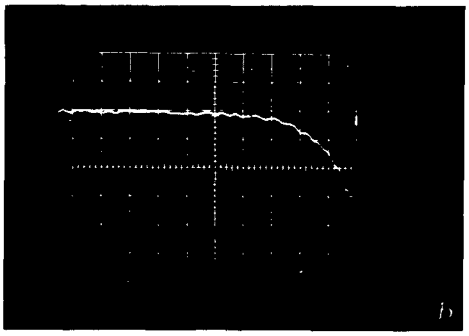
Pressure



Time

a. Low Pressure Wafer Gage 0.003 psia,
2 msec/Horizontal Division

Pressure



Time

b. Low Pressure Wafer Gage 0.05 psia,
500 μsec/Horizontal Division

Fig. 16 Low Pressure Wafer Gage Response Traces

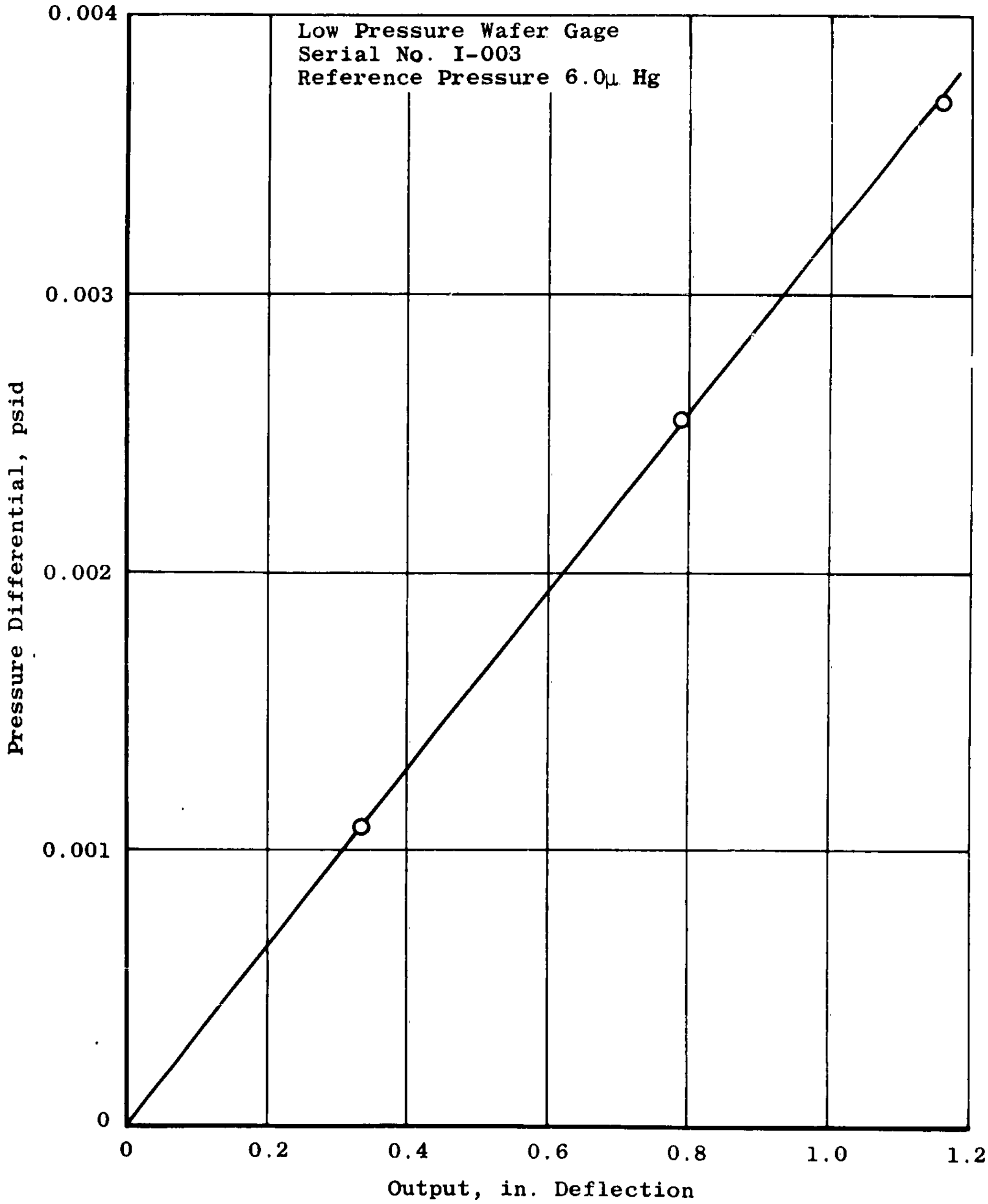


Fig. 17 Low Pressure Wafer Gage "in Tunnel" Calibration

Note: Pressure ports on accelerometer are attached to pressure transducer reference system to ensure zero pressure differential in accelerometer. These ports also provide a means to check out the accelerometer.

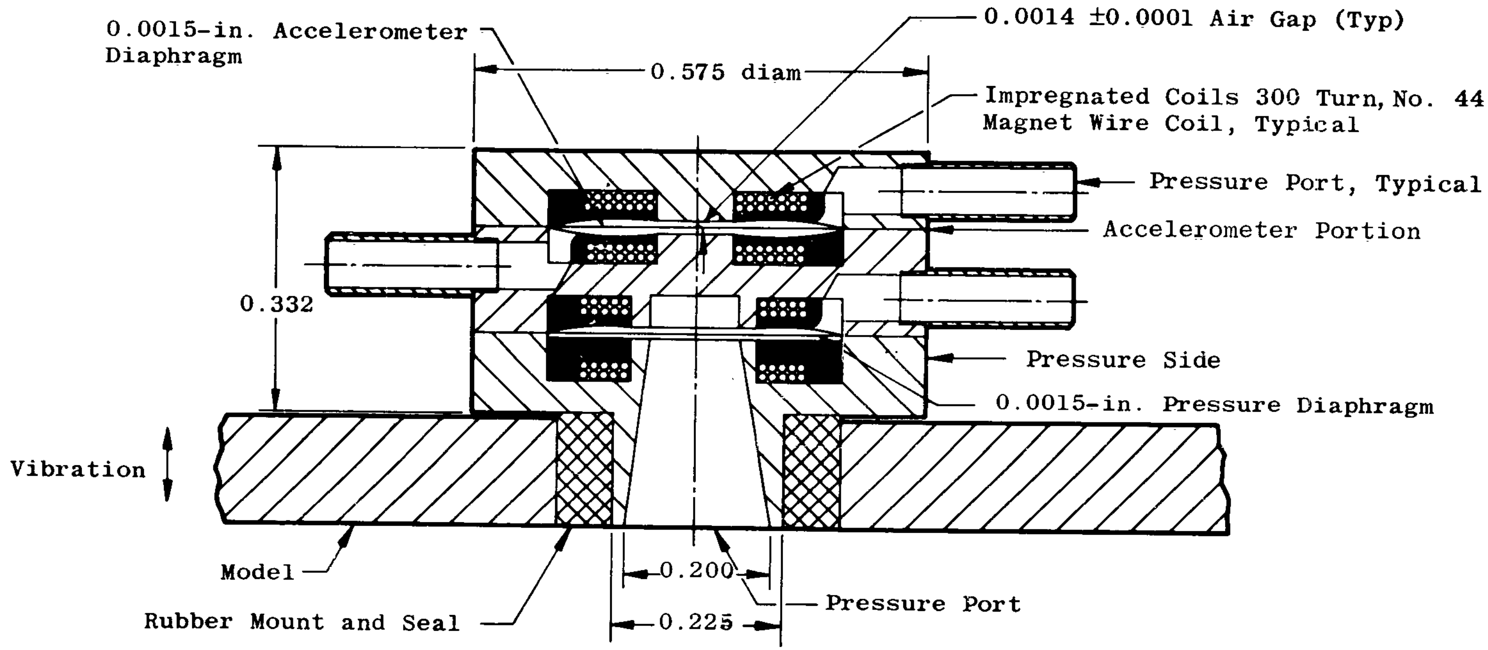


Fig. 18 Assembly Section of Low Pressure, Acceleration Compensated Transducer

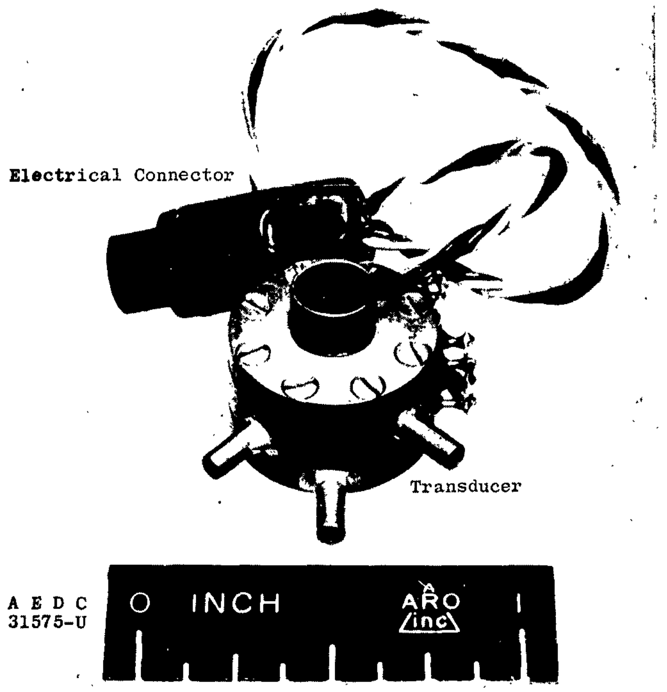


Fig. 19 Low Pressure, Acceleration Compensated Transducer

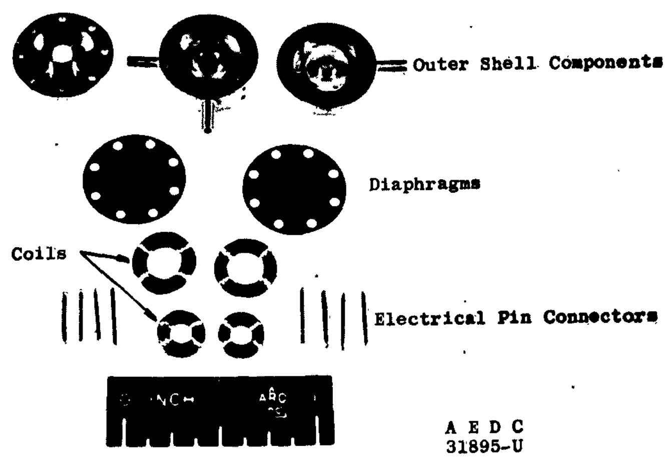


Fig. 20 Acceleration Compensated Transducer Components

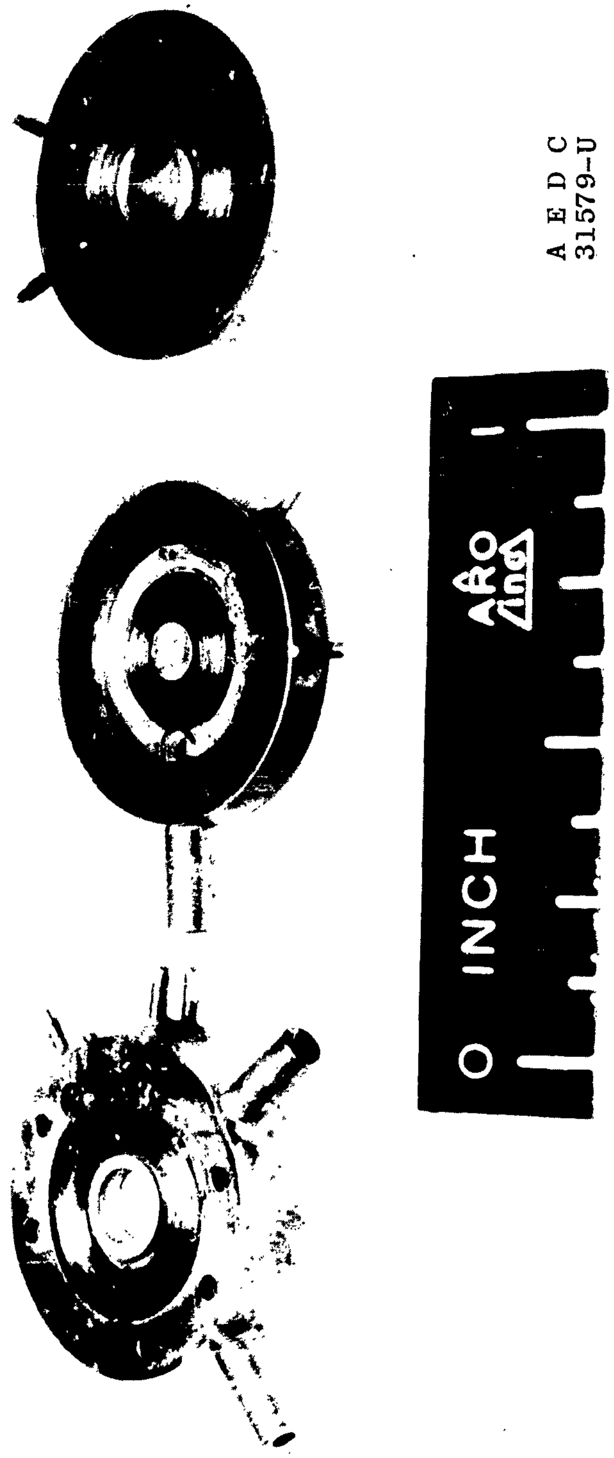


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Fig. 21 Acceleration Compensated Transducer Outer Shell Components with Embedded Coils

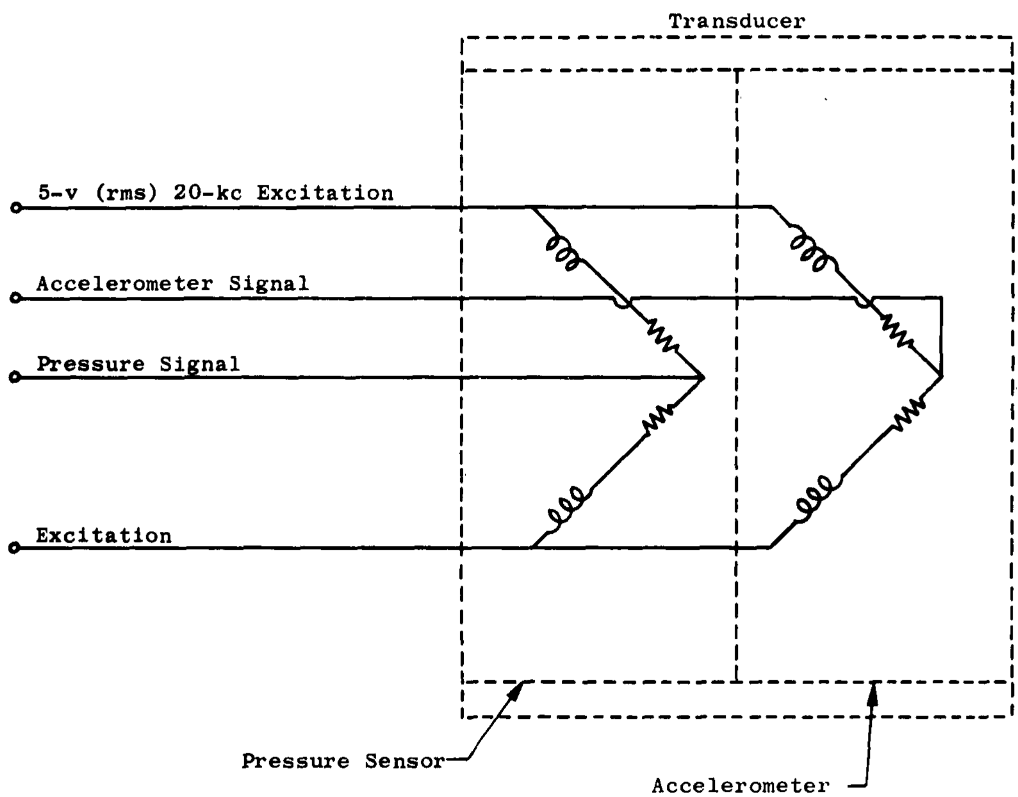


Fig. 22 Low Pressure, Acceleration Compensated Transducer Schematic

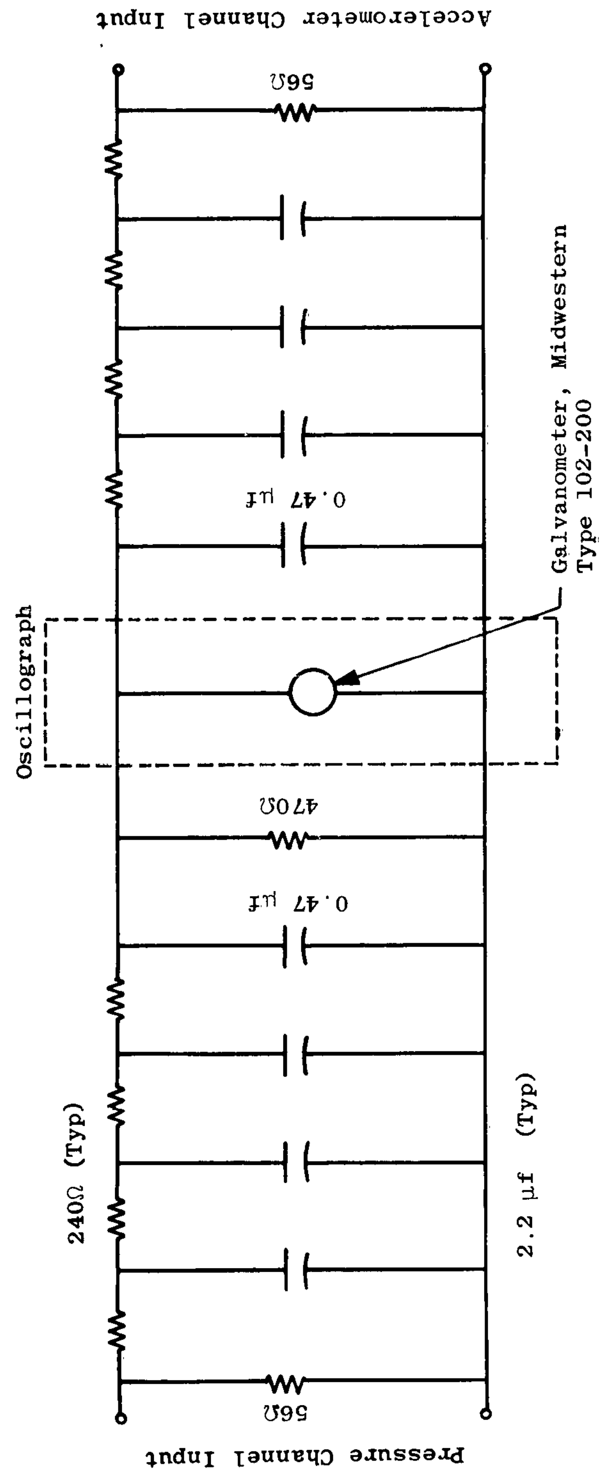
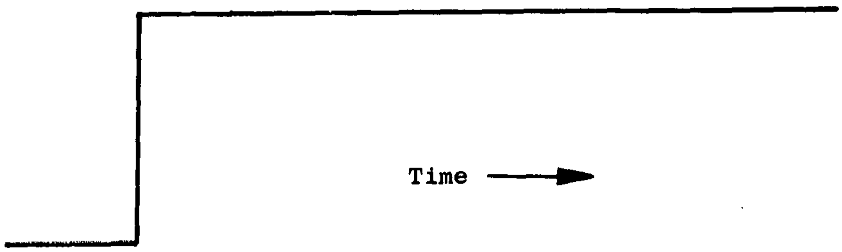
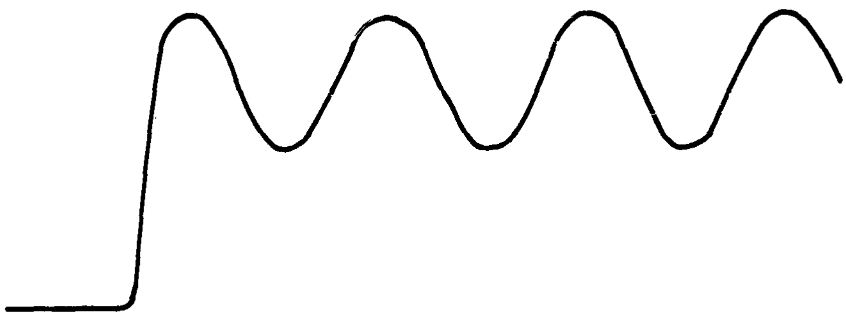


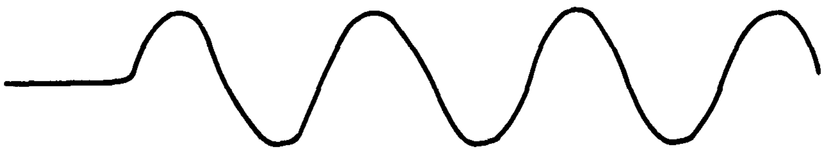
Fig. 23 Summing and Filtering Network



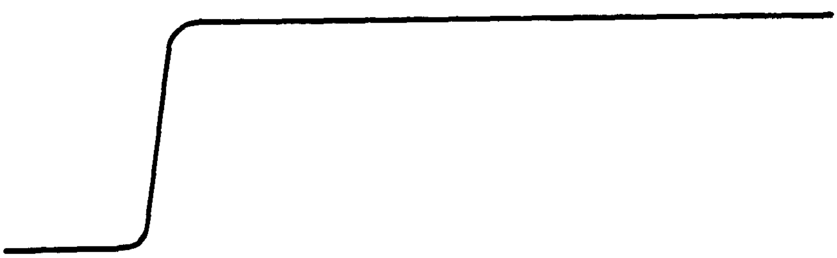
a. Pressure Function



b. Pressure Transducer Response to Pressure Function plus Superimposed Transducer Vibration



c. Accelerometer Response to Transducer Vibration



d. Sum of Pressure Transducer and Accelerometer with Proper Phasing

Fig. 24 Acceleration Compensating Theory

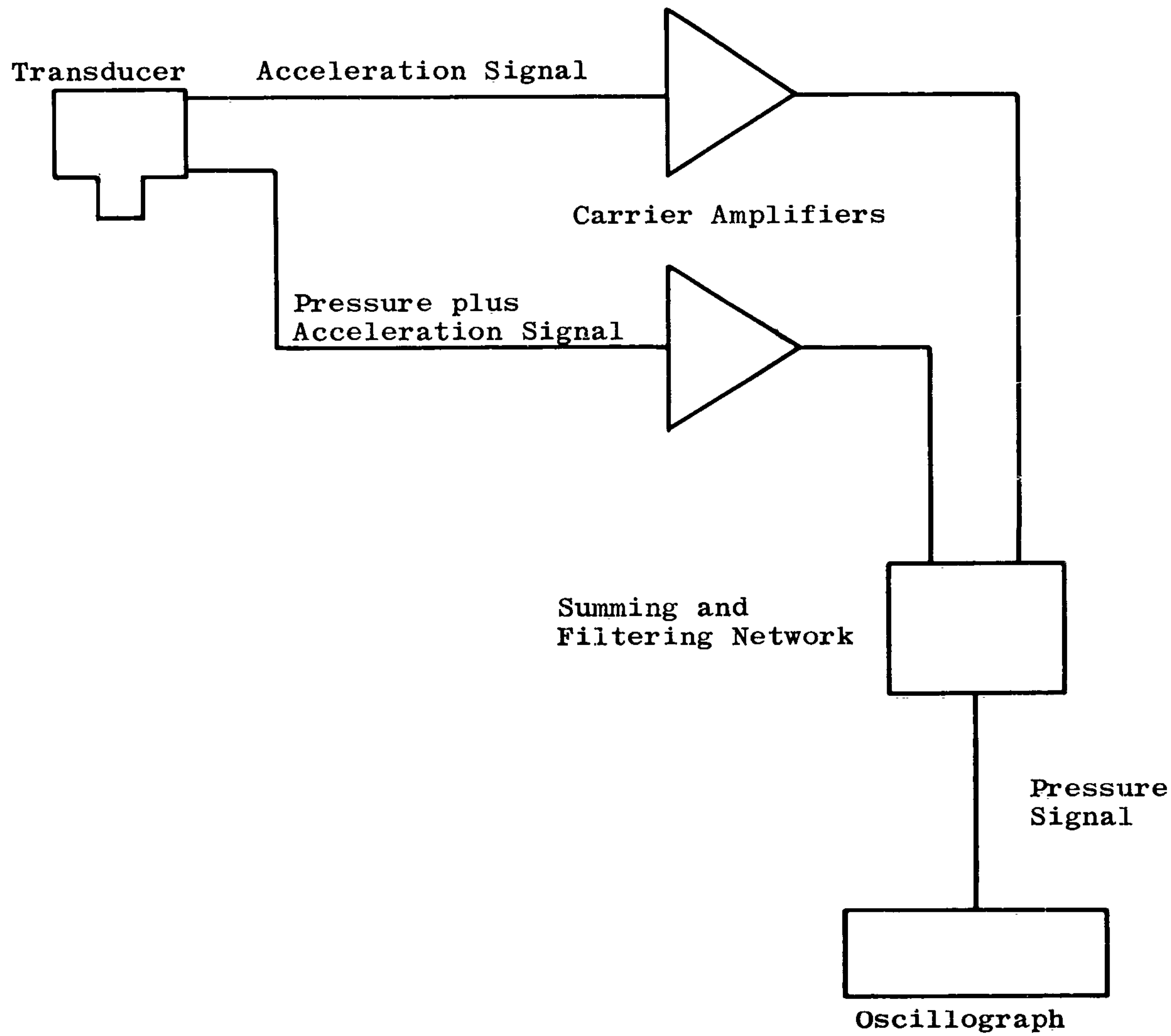


Fig. 25 Low Pressure, Acceleration Compensated Transducer Instrumentation System

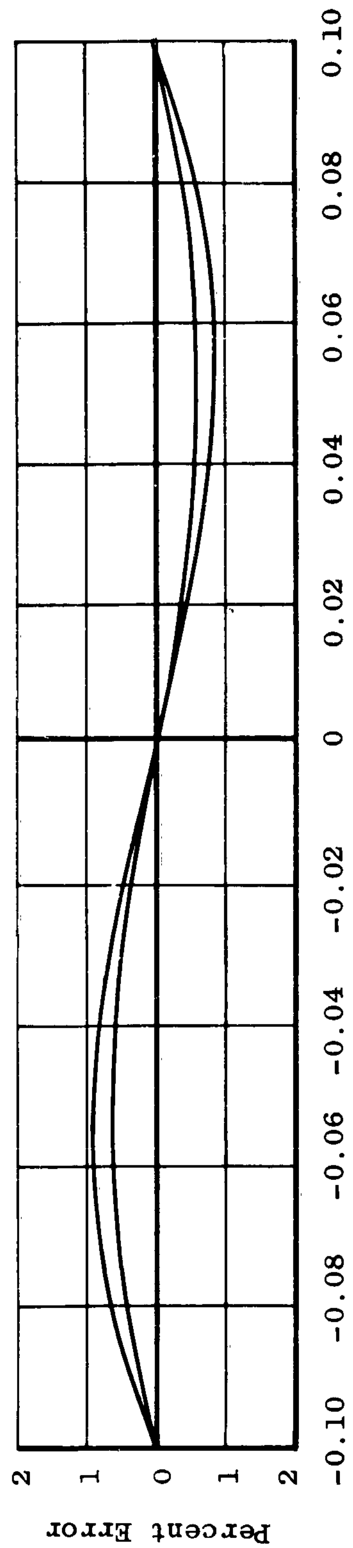


Fig. 26 Acceleration Compensated Transducer Linearity and Hysteresis

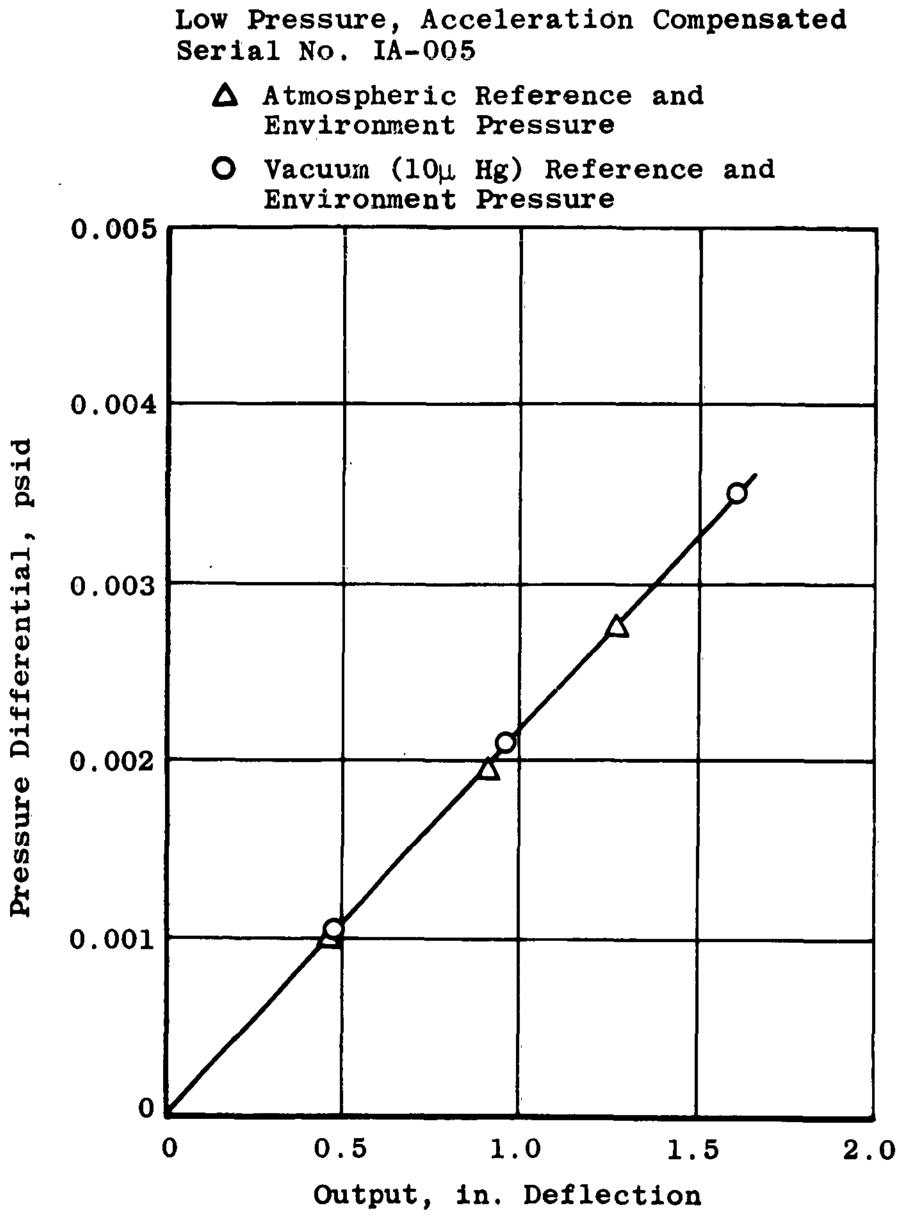


Fig. 27 Effect of Density Level on Transducer Output

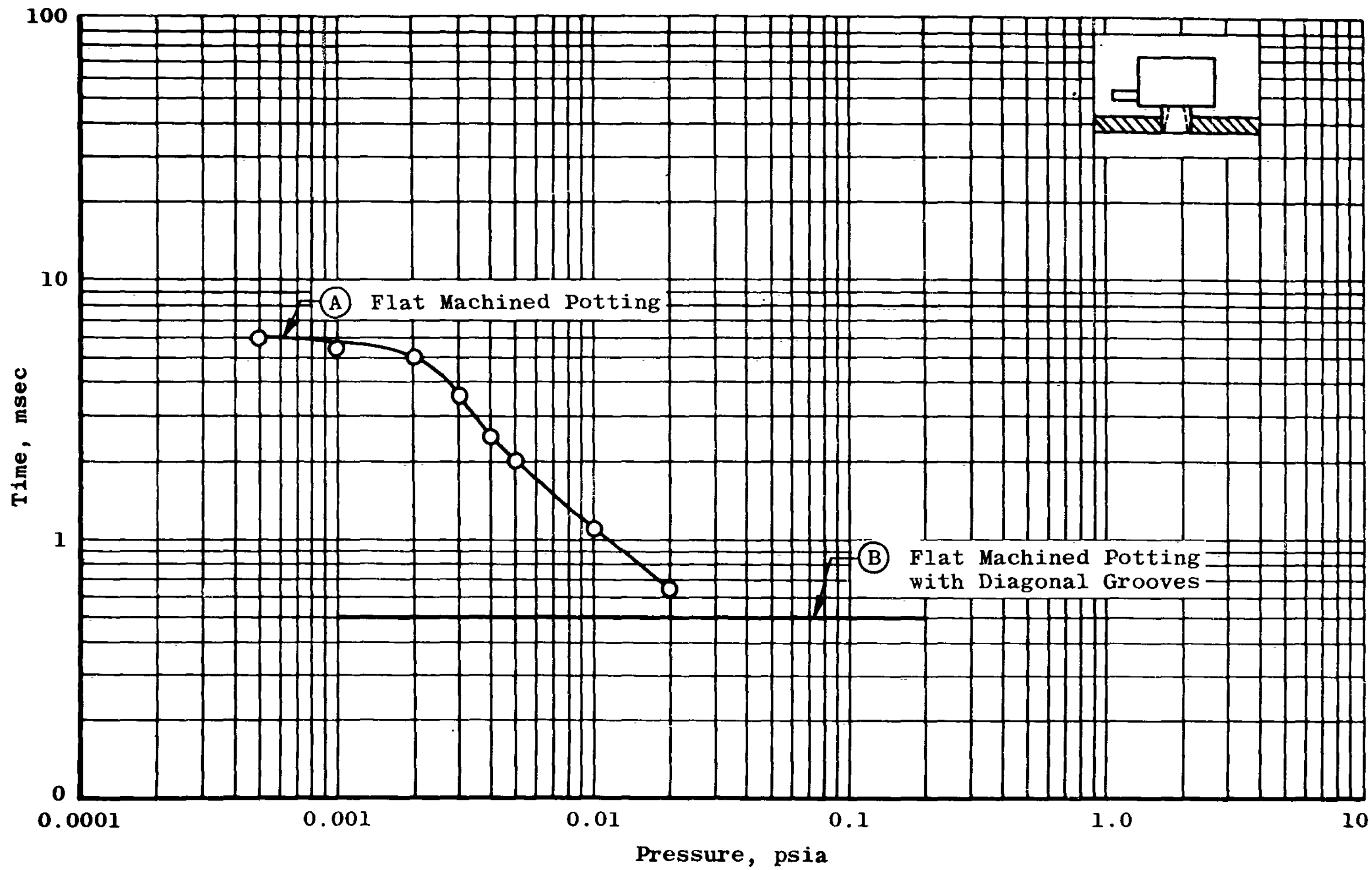


Fig. 28 Low Pressure, Acceleration Compensated Transducer and Associated Instrumentation Response Time

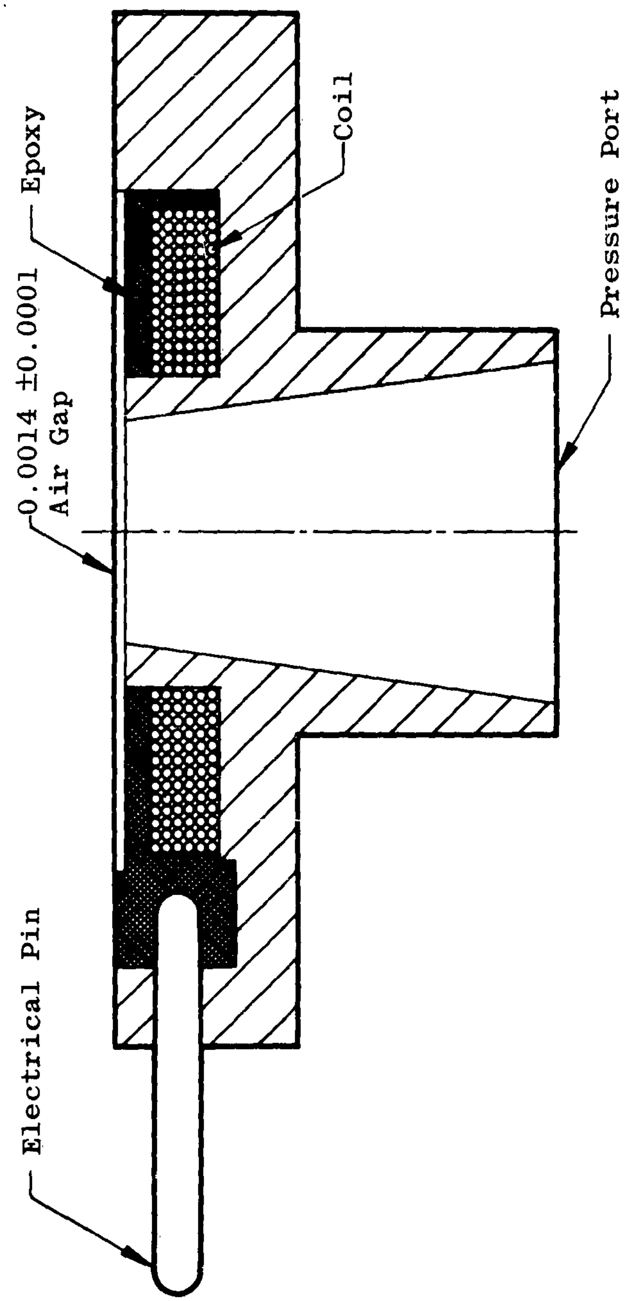


Fig. 29 Acceleration Compensated Transducer with Machined Potting

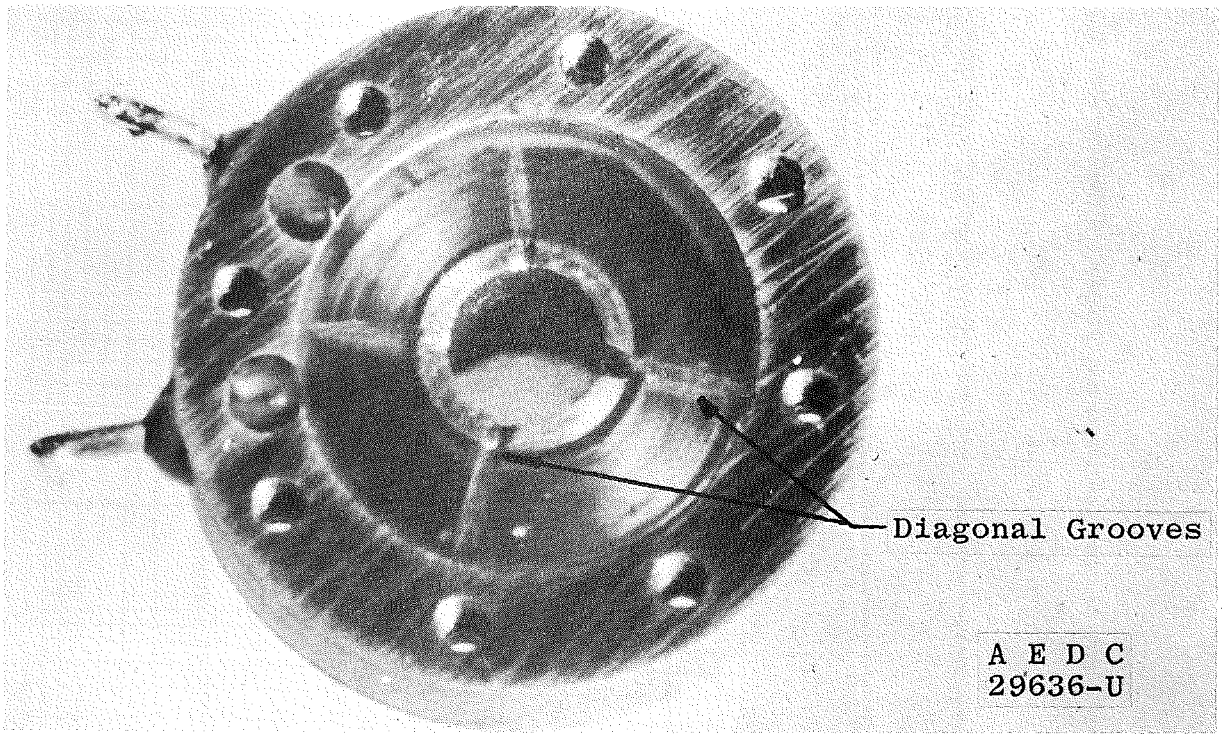
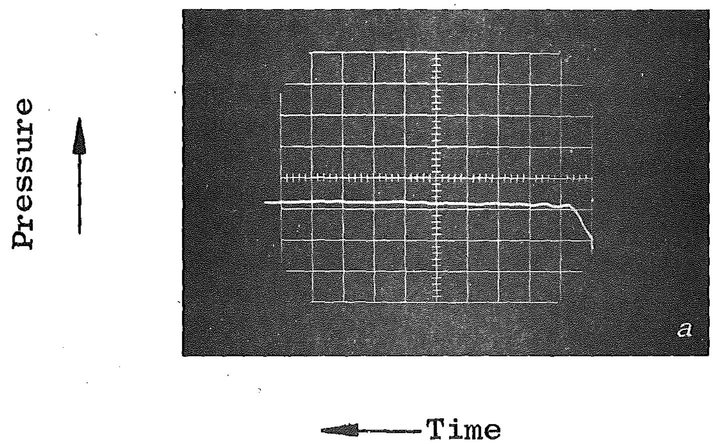
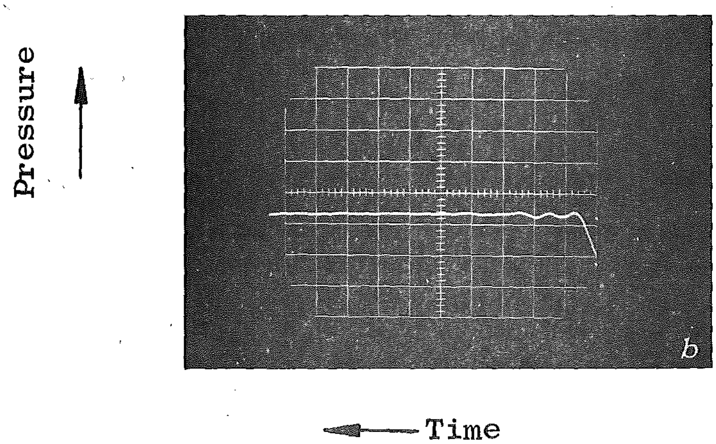


Fig. 30 Acceleration Compensated Transducer with Grooved Potting and Core

Configuration "B" in Fig. 28



a. Acceleration Compensated Transducer, 0.002 psia, 500 μsec/Horizontal Division



b. Acceleration Compensated Transducer, 0.10 psia, 500 μsec/Horizontal Division

Fig. 31 Acceleration Compensated Transducer Response Traces

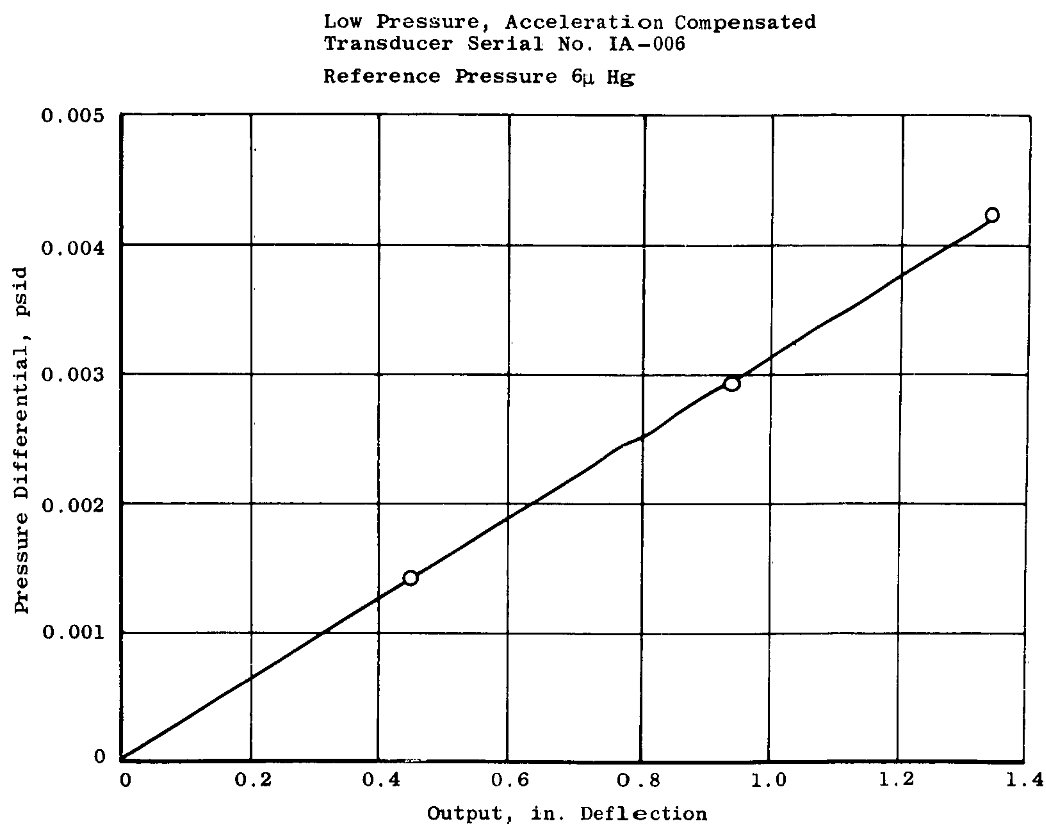
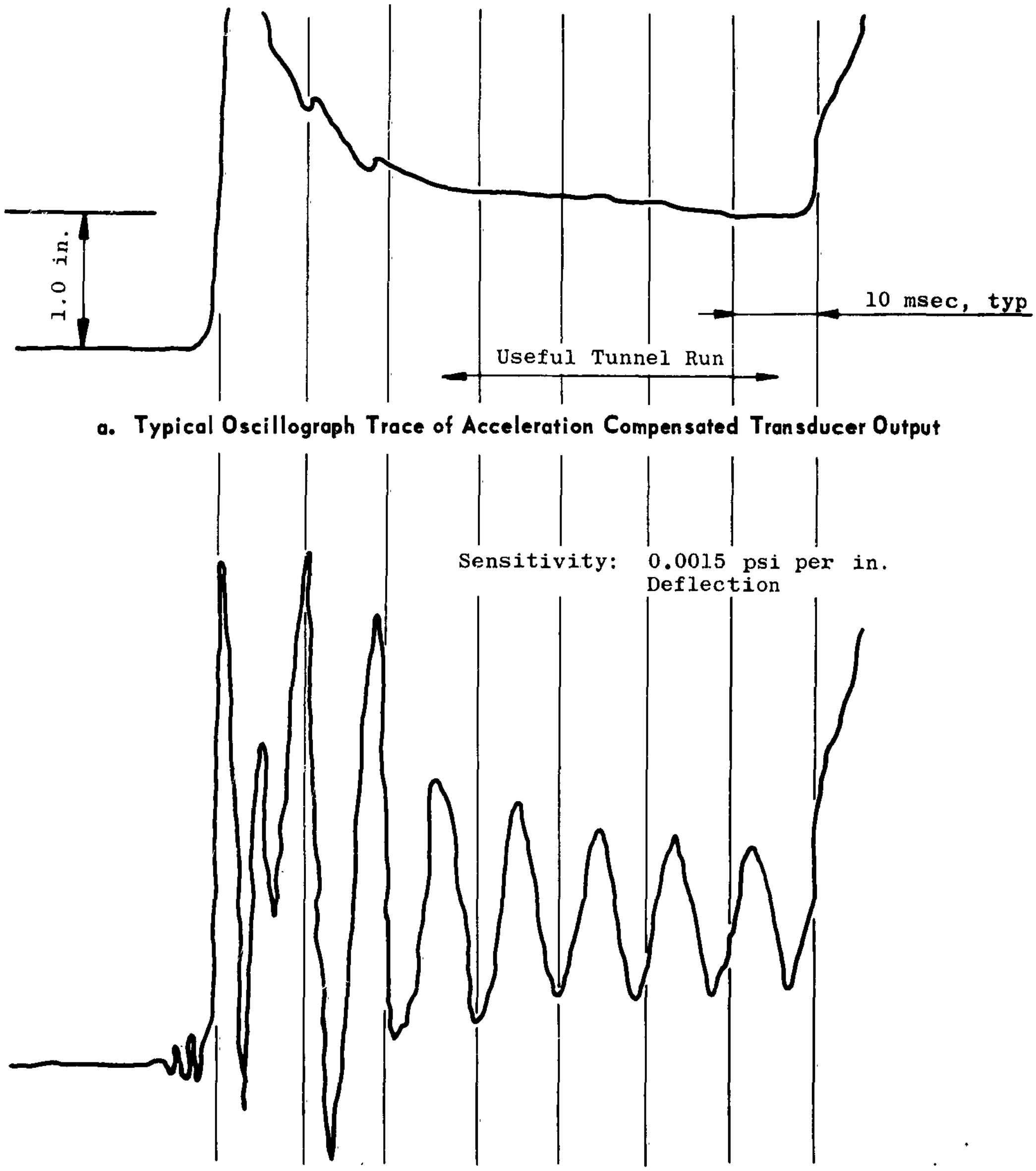


Fig. 32 Acceleration Compensated Transducer "in Tunnel" Calibration



a. Typical Oscillograph Trace of Acceleration Compensated Transducer Output

b. Uncompensated Pressure Trace

Fig. 33 Comparison of Acceleration Compensated and Uncompensated Transducers